Experiments in randomly agitated granular assemblies close to the jamming transition

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We present here the preliminary results obtained for two experiments on randomly agitated granular assemblies using a novel way of shaking. First we discuss the transport properties of a 2D model system undergoing classical shaking that show the importance of large scale dynamics for this type of agitation and offer a local view of the microscopic motions of a grain. We then develop a new way of vibrating the system allowing for random accelerations smaller than gravity. Using this method we study the evolution of the free surface as well as results from a light scattering method for a 3D model system. The final aim of these experiments is to investigate the ideas of effective temperature on the one hand as a function of inherent states and on the other hand using fluctuation dissipation relations.

1. Introduction

Strikingly, systems as different as dense emulsions, colloidal pastes, foams or granular matter have many rheological properties in common [1]. All these systems can flow like fluids when a sufficiently high external stress is applied but jam into an amorphous rigid state below a critical yield stress. This jamming transition is associated with a slowdown of the dynamics which led Liu et al. [1] to propose an analogy between the process of jamming and the glass transition for glass-forming liquids. Although the nature of this jamming transition is still unclear experimentally [2], several attempts were made to adapt the concepts of equilibrium thermodynamics to athermal systems out of equilibrium [3, 4, 5, 6, 7, 8]. For packings made of grains with a size larger than a few microns, thermal fluctuations are too small to allow a free exploration of the phase space. The grains are trapped into metastable configurations. The system can not evolve until external mechanical perturbations like vibration [9] or shear [10] are applied allowing the grains to overcome energy barriers and triggering structural rearrangements. In this case, the free volume and the configurations accessible for each grain are capital notions that were used to define the new concept of "effective temperature" [3]. It was proposed

recently that this notion could account for the transport properties in the vicinity of a jammed state through a fluctuation dissipation theorem [4].

A. Fierro *et al.* [11] treat this question in analogy with supercooled liquids. In this case we understand by inherent states those that do not evolve with time and that correspond to the local minima of the potential energy in the 3N-dimensional configuration space of the particle coordinates. A. Fierro et al. [11] now consider the mechanically stable states of granular materials at rest as inherent states. They work numerically with a 3D system of hard spheres subject to gravity and undergoing a Monte-Carlo shaking. During the dynamics, the system cyclically evolves for a time τ_0 (corresponding to the tap duration) at a finite value of the bath temperature T_Γ (corresponding to the tap amplitude) and is suddenly frozen at zero temperature in one of its inherent states. They find that the system reaches a stationary state determined by the tap dynamics (i.e. different T_Γ and τ_0). These stationary states are indeed characterized by a *single* thermodynamical parameter since one finds a single master function when the fluctuation $\overline{\Delta E^2}$ is plotted as a function of $\overline{E}$, where E is the potential energy of the ensemble of grains. Based on this result, they conclude that the quasi-stationary state can be genuinely considered a"thermodynamical state" and they define an effective temperature through the fluctuation-dissipation relation.

Here we design an experimental set-up with the final aim to test closely the ideas of effective temperature on the one hand as a statistics of inherent states and on the other hand as a result of the fluctuation-dissipation relation by studying the transport properties of a grain. Contrarily to previous work on vibrated granular assemblies, we design a new way of shaking the granular material at accelerations much lower than gravity. In the first part of the paper, we study a model granular assembly in 2D and use this preliminary investigation to design the final 3D experiment. The preliminary results obtained with this set-up are presented in the subsequent section.

2. Vibration of a 2D model granular assembly

2.1. Experimental Set-Up

We study the displacement of tracer particles in a 2D model granular assembly which is exposed to tapping. To do so we use the following model system (figure 1): a layer of polydisperse particles is confined between two vertical glass plates. The dimensions of the glass plates are 20 cm times 30 cm. The lateral walls are made of Teflon. We use a mixture of small cylindrical steel particles of 3 mm height with three different diameters, notably $d_1 = 6$ mm, $d_2 = 5$ mm and $d_3 = 4$ mm to create a disordered packing. The cell is partially filled which leads to about 30 particles in the vertical direction and to 60 particles in the horizontal direction.

We now study the response to tapping of the system by using an electromagnetic shaker. A single sinusoidal tap is applied every 5s. The subsequent motion of the shaker and the beads lasts about 1 s. Note that we can vary the intensity of the tapping by changing the applied voltage from 100 mV to 500 mV leading to accelerations from approximately $\gamma_{peak}/g = 1$ to $\gamma_{peak}/g = 2$, with γ_{peak} being the peak acceleration. The system contains between 1 to 3 tracer particles of diameter $d_1 = 5$ mm that can be positioned at a given initial position. A CCD camera coupled to a computer captures a picture after a given

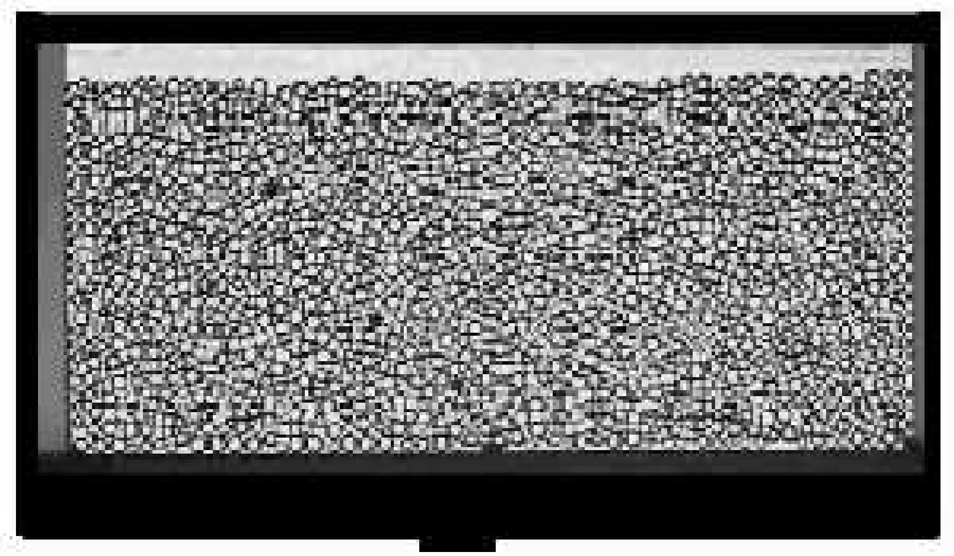

Figure 1. Experimental set-up showing the 2D model system for a granular assembly under vibration: a layer of polydisperse particles is confined between two vertical glass plates. A single sinusoidal tap is applied every 5 seconds via an electromagnetic shaker.

number of taps (typically between 500 to 1000 taps) and allows us to follow the long time displacements of the tracers. We then extract the trajectories of the tracer particles using image processing and finally obtain their x and y coordinates as a function of time.

Note that we typically observe a compaction of the initial surface occupied by the grains of about 1% during the first 10000 taps, that correspond to the very beginning of our experiments. Afterwards we observe fluctuations of the height of the granular layer but can not detect further compaction within our experimental resolution.

2.2. The large scale and long time convection dynamics

In the following, we describe the experimental results obtained when performing experiments with a free surface at the top of the granular assembly. In this case, for accelerations larger than the acceleration of gravity and for a given phase of the motion, the grains on the upper surface are launched freely with an upwards velocity given by the acceleration of the cell. A bit later an impact with the rest of the granular assembly occurs as the latter catches up with the grains at the upper surface [12]. In the absence of boundaries all grain would follow about the same free flight trajectories. This holds only if the grains come to a complete rest between two taps and thus provided that the time for energy dissipation is smaller than the time between two impacts. The sequence of impacts is at the origin of the more or less random shaking of the granular assembly and subsequently, is triggering the compaction/decompaction phenomenology.

The problem is that this shaking procedure is strongly complicated by the presence of frictional boundaries which are in our case the lateral walls made of Teflon. The motion of the grains in contact with the boundaries is perturbed by friction and for

vertical boundaries these grains hit the rest of the assembly slightly before their neighbors positioned further away from the boundaries. This leads to a slow but inexorable descent of the grains at the boundaries since these grains are likely to occupy the empty space left by their neighbors still in free flight. Because of mass conservation, the compound of this motion, tap after tap, leads to large scale convection rolls [13, 14, 15].

Furthermore, the magnitude of the convection rolls depends not only on grain/boundary friction values [15] but also on the packing density values. The reason is that the higher the packing fraction, the more efficient is the transmission of vertical forces to horizontal forces (given by the Janssen's effective parameter : see [16]). This effect, in association with the friction coefficient, fixes a limit between an upper part where the convection rolls are located and a bottom part which is blocked since the boundary grains cannot overcome the Coulomb threshold. It was show by a simple argument that this effect of a jammed phase localization depends on the aspect ratio of the cell, it is reduced in the limit of small friction and is bound to disappear for maximal accelerations larger than $2g$ [17].

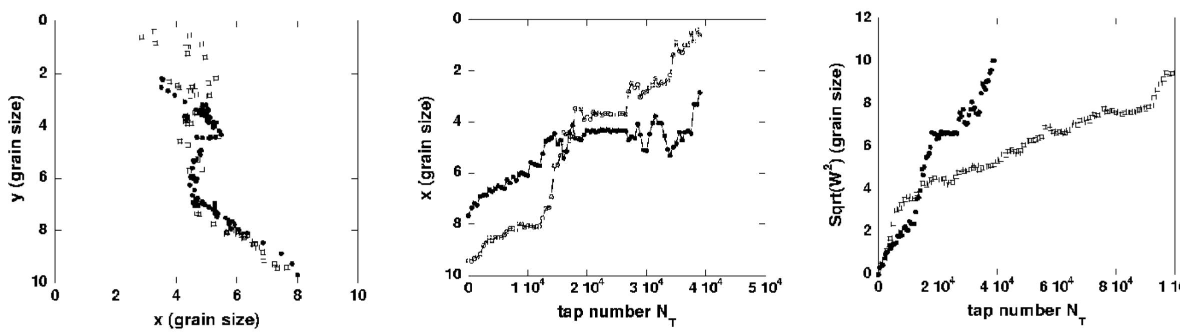

Figure 2. Tracer displacement for two experiments having the same initial configuration but different tapping amplitudes, given by the applied voltage of 150 mV for experiment 1 and 325 mV for experiment 2. For experiment 1 a snapshot is taken every 1000 taps and for experiment 2 every 500 taps. All displacements are scaled on a typical grain size of 5 mm. The observed tracer is placed in the middle of the celle at the beginning of the experiments. Left: Trajectory of experiment 1 (□) and experiment 2 (•). Middle: x (•) and y (∘) coordinate for experiment 2 as a function of the tap number. Right: $\sqrt{\langle W^2 \rangle}$ as a function of tap number for experiment 1 (□) and experiment 2 (•)

First, we describe two experiments having the same initial configuration but different tapping amplitudes. The steel grains are chosen to have a low friction with the Teflon boundaries such that for all the experiments we show, we do not observe a phase where the convective motion is blocked in the bottom part. The experiment with the lower tapping amplitude is experiment 1 whereas the experiment at a higher tapping amplitude is experiment 2. The left graph of figure 2 shows the trajectories of the tracer for the two experiments. The displacement is scaled on an average grain size of 5 mm. One observes that the tracers follow in both cases the same trajectory, signature of a convective motion

without significant diffusion of the particles. Note that for experiment 1 a snapshot (corresponding to one data point) is taken every 1000 taps whereas for experiment 2 a snapshot is taken every 500 taps. The velocity of the tracer is thus different from one experiment to another as one would expect. Even if the two trajectories seem quite smooth, the displacement of the tracer as a function of time is very irregular. This is illustrated on the graph in the middle of figure 2 that shows the x and y coordinates of experiment 2. We have observed for several experiments, that the tracer does nearly not move for a large number of taps and then abruptly continues its displacement. The graph on the right side of figure 2 finally shows $\sqrt{\langle W^2 \rangle}$ the sliding average of the root mean square displacement for experiments 1 and 2. This graph shows clearly that the displacement as a function of the number of taps is less important for experiment 1 than for experiment 2. Furthermore, it becomes again clear from this graph that large scale convective displacements are taking place in the granular assembly. An estimation of the average particle velocity observed in our experiments leads to values roughly between $v_{particle} \sim 1$ particle size per 1000 taps or even per 10.000 taps depending on the applied voltage. Interestingly, for grains of typically the same size, Philippe et al. [18] find the same order of magnitude for their 3D tapping experiment. Note, that the convection velocity increases with the tapping amplitude.

The importance of the large scale displacements becomes even more clear when looking at a third experiment (experiment 3). In this case, the tapping amplitude was increased further and three tracer particles were followed. A snapshot was taken every 500 taps. On the left of figure 3 one can see the trajectories of two of the three particles and one can conclude that huge convection rolls form in the system. Note that the convection roll observed occupies half the size of the cell. After one period the particle follows nearly the same trajectory again. This is illustrated on the right graph of figure 3 that shows the x and y coordinates for one of the particles as a function of the number of taps. One may notice that they follow nearly a perfect sinusoidal motion over more than one period. Once again one can conclude that the motion is purely convective.

Consequently, it is clear from these model experiments that the leading dynamical behavior for the shaken grains is convection with grains following well defined trajectories. Even if for low shaking amplitudes we have intermittent dynamics as seen on figure 2 (middle) we did not observe any significant diffusive motion of the grains. In other words, the grains are likely to keep their neighbors for a very long time. Thus, any attempt to characterize the compaction dynamics by self diffusive properties of the grains, is doomed to fail. Another important question that one could rise, is whether the observed convection dynamics is related to the steady states reported experimentally in tapping experiments [9, 18, 19, 20, 21]. One might suggest that the convection rolls lead to a decompaction of the system and that there is thus a competition between this decompaction and compaction due to shaking. This could explain the different results reported by Nowak and Knight *et al.* [9, 20, 21] and Philippe et al. [18, 19] since they use columns with different aspect ratios. Moreover, the column by the Chicago group is very narrow (about 15 grains across) and the role of wall friction and finite size effects could then be crucially important. All these questions are to us still open.

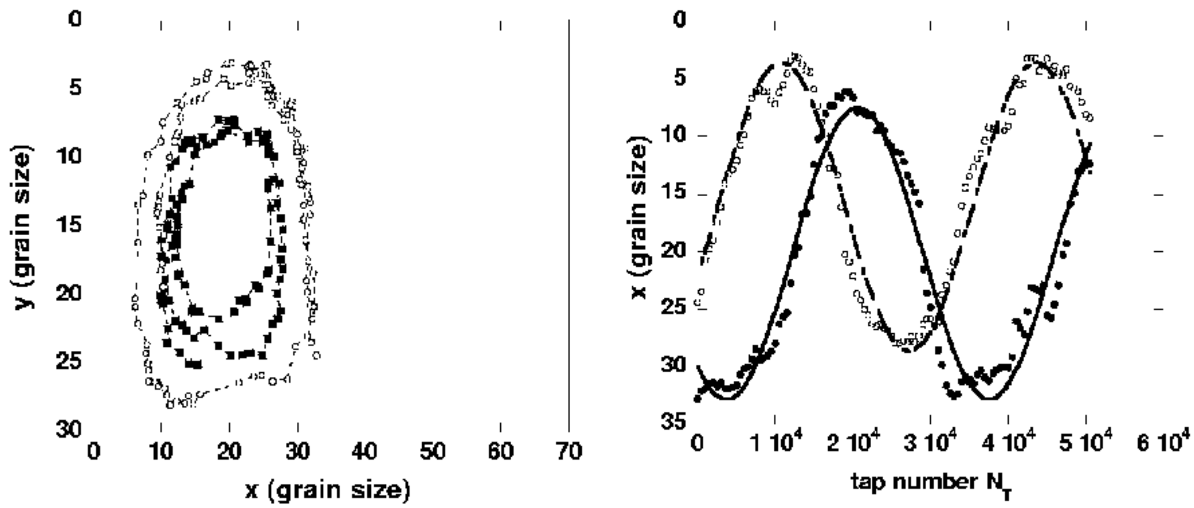

Figure 3. Tracer displacement for experiment 3 with a high tapping amplitude (500 mV). A snapshot is taken every 500 taps. Left: Trajectories of tracer 1 (■) and tracer 2 (○) showing huge convection rolls. Right: x and y coordinate of tracer 2 as a function of N_T.

2.3. Suppression of convection

We now try to suppress the convection by putting a lid on top of the cell at a distance of less than one bead diameter. The idea is to produce a bounce of the grains on the lid almost immediately after the launch of the packing. This bounce downwards is likely to suppress the time lag effect in the grain trajectories due to the presence of walls with friction.

The results obtained are indeed significantly different from those with a free surface. A direct visualization of the packing witnesses a rather strong agitation of the grains: one can note rather pronounced collective motions of the grains where large assemblies of particles seem to oscillate very slowly. A closer look at the trajectories (figure 4 left) shows however that these trajectories are clearly localized. Note that all displacements shown on this graph are less than one particle diameter, even for very long times. Note that the bottom tracer is close to the bottom plate which explains its slightly stronger agitation. Figure 4 (right) shows the trajectory of the upper tracer in detail and one can conclude once more that the displacement of the grains are very small. From figure 5 that shows $\sqrt{\langle W^2 \rangle}$ one can conclude that once again we do not observed any significant self diffusion of the particles but that in this case the displacement is localized. Note that the strongest displacement is seen for the bottom tracer as explained above.

Therefore, when the convection is suppressed, we still observe modes of motion of the packing that can lead to reorganization and compaction but it is clear now that those modes are collective and are not associated to self-diffusion properties of a grain.

2.4. Outlook

In the previous sections we have shown that when applying strong tapping ($\gamma_{peak}/g > 1$) to a 2D granular assembly, strong convection takes place. This convection can be

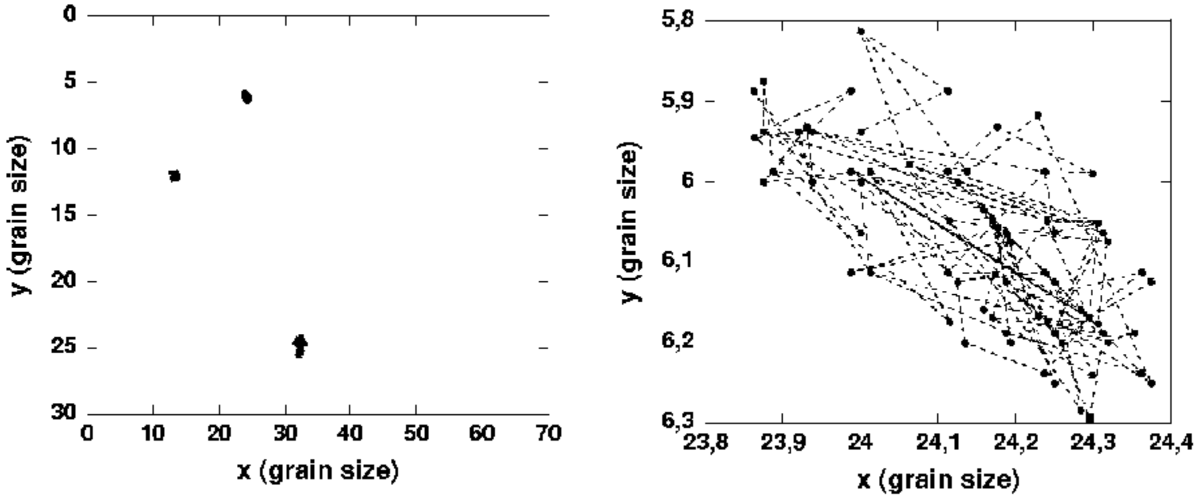

Figure 4. Displacement of three tracer particles for experiment 4, having the same initial configuration and tapping amplitude as experiment 3, but with a lid on top. Left: Trajectory of three tracer particles. Right: Trajectory of one of the tracer particles (the upper particle) in detail.

suppressed by putting a lid on top of the granular assembly, but then the position of the lid has to be finely tuned. A lid too close to the packing may suppress drastically the granular motion and for a lid too far away may start convection again. Clearly, this is not a method suited to study a problem where compaction i.e. the packing height, may vary.

Thus, we suggest to study a different system, that might allow to suppress convection in a more adequate way and might thus be better adapted to study the dynamics and the transport properties of an agitated packing of grains. To do so, we have built a set-up where a large number of individually controlled pistons are moving up and down at the bottom of a cell identical to the one described in section 2.1. The individual control of the pistons allows to go from spatially and temporally coherent to more complex agitations. Furthermore, lower tapping amplitudes can be applied such that $\gamma_{peak}/g < 1$ which will also suppress convection. We plan to measure the displacement of one or several tracers as well as the collective modes of reorganization, and to measure the mobility of a tracer when a given constant force is applied. A way to do this is to use a denser particle or design a way to pull the tracer. Further more we plan to measure the fluctuations of the free surface. The results will then be compared to the results obtained in 3D that will be described in the following.

3. Compacting a 3D granular assembly

The experimental set-up in 3D is set to create in the bulk a random agitation of the grains at low level of energy and in conditions where convection rolls due the uplift of the grains are completely suppressed. Following the results of the 2D model system

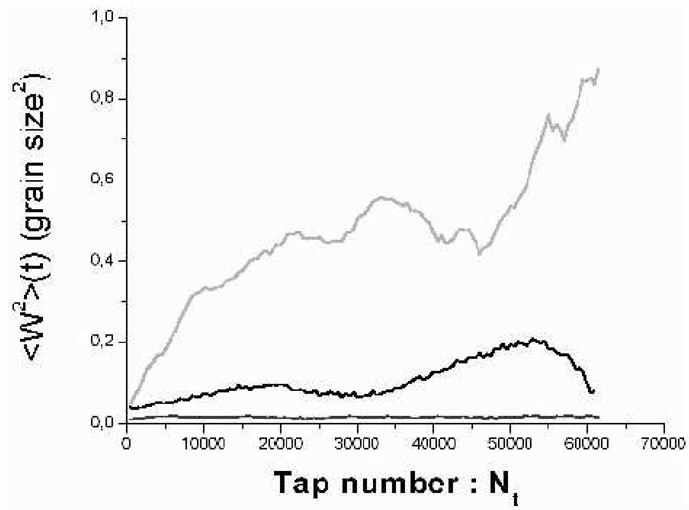

Figure 5. $\sqrt{\langle W^2 \rangle}$ as a function of tap number for the three tracers of experiment 4. The two curves with the lower displacement correspond to the two upper tracers whereas the curve with the highest displacement corresponds to the bottom tracer.

presented in the previous section, we seek to produce an influx of energy creating a quasi randomly agitated surface in connection with the bulk of the packing. This is the closest we could think of a "thermal bath". The practical method is described in the next subsection. Then, we expose some preliminary results showing that the method is encouraging and might well be suited to study compaction and jamming processes in granular assemblies and also leads to a path where the notion of effective temperature can be precisely addressed.

3.1. Experimental set-up

The vibration device is made of five piezoelectric transducers commercially sold as a part of a tweeter. As shown in figure 6, the transducers are at the bottom of a conical shape paper container which is filled with $1.5mm$ glass beads. The surface of the granular packing confined inside the tweeters is fixed to the observation cell and constitutes its bottom. The cell is a hollow rectangular box of $20cm$ length, $2.3cm$ width and around $4cm$ high. The front and rear boundaries are made of glass. The piezos are excited by a $380Hz$ square signal with a maximum effective voltage $V_{eff} = 35V$ (figure 6). The resonance frequency of each piezo is $f_0 = 1200HZ$. Note that the power that each piezo dissipates is enough to make a single and lonely grain on the piezo fly up to $5mm$ high. However, when the box is filled with grains (around $350g$), the grain motion induced by the piezos is so small that it is not perceptible to the eye.

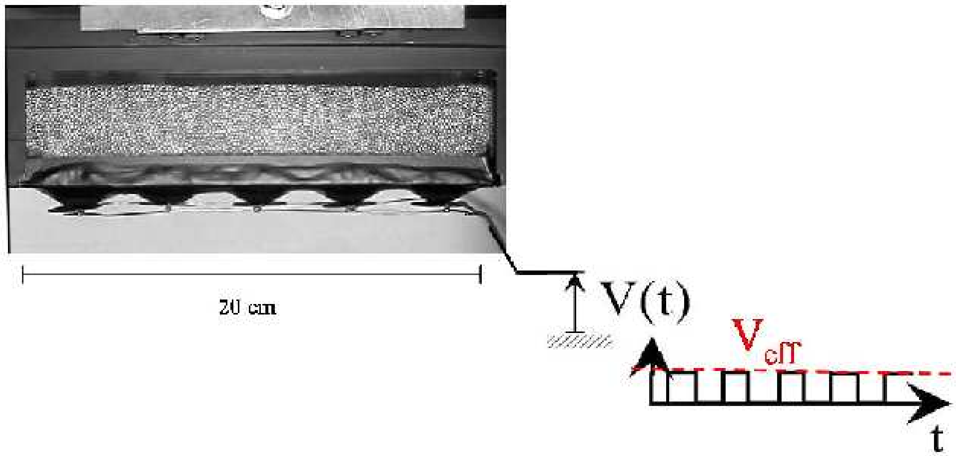

Figure 6. Experimental set up: five piezoelectric transducers constitute the bottom of a rectangular glass box which is filled with $1.5mm$ glass beads. The piezos are excited by a $380Hz$ square signal with a maximum effective voltage $V_{eff} = 35V$

3.2. Measurement techniques

The cell is instrumented to measure several things (see figure 7) : (i) an inductive probe provides the position of a thin metallic plate lying on the top granular surface and gives information about the mean **compaction or the potential energy** of the packing, (ii) an accelerometer buried in the granular packing provides informations on the **effective injected power** (iii) we use a Diffusing Wave Spectroscopy (DWS) technique to measure the **characteristic times involved in the microscopic dynamics** [22], (iv) finally, the cell is also designed to evaluate the **mobility** of an intruding grain. This last point will be described more precisely in the last subchapter.

The basic idea of DWS is to make a coherent light (laser) pass through a scattering sample in which each photon is elastically scattered multiple times in such a way that it performs a random walk. Under this circumstances, the light diffuses through the sample and forms an interference pattern after it. The microscopic dynamics of the grains are related to the dynamics of the light interference pattern. Here, a multispeckle technique is used that was developed earlier for colloids. The system dynamics assessment is made through the computation of the light intensity autocorrelation function:

$$g_2(t_w, t_w + t) \equiv \frac{\langle I(X,Y,t_w) I(X,Y,t_w+t)\rangle_{X,Y}}{\langle I(t_w)\rangle_{X,Y}\langle I(t_w+t)\rangle_{X,Y}} - 1 \tag{1}$$

where t_w is the time of the reference image, t is the time relative to t_w and (X, Y) are the spatial coordinates on the speckle image. The theory of light diffusion shows that under the regime of multiple scattering (where the photons perform a random walk) it is possible to quantitatively relate the characteristic correlation time of g_2, τ, to the mean displacement of the grains (scatterers) [22]. However, in our case, preliminary measurements show that due to the relatively small number of grains across the cell

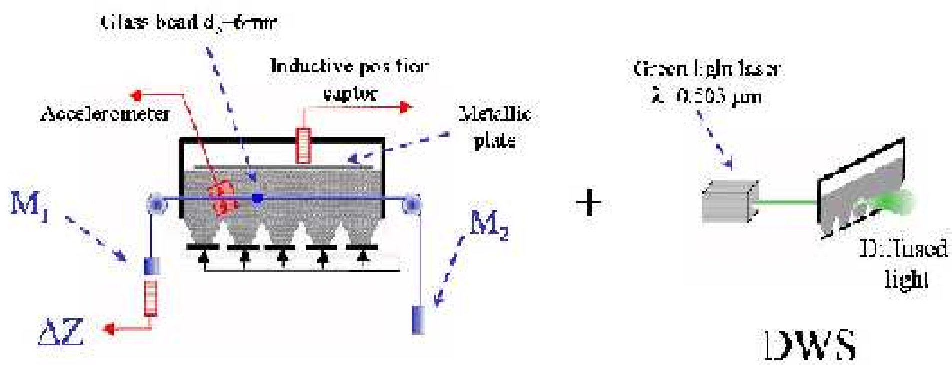

Figure 7. We can measure in the system: the compaction or potential energy, the effective injected power, the characteristic microscopic time (DWS technique) and the mobility of a grain.

(about 14 grains), the condition of a fully developed random walk for the light path is probably not fully achieved and thus, the possibility to trace back quantitatively the average motion of the grains is somehow complicated. On the other hand, at this stage, the correlation function is still a good and sensitive indicator for the granular dynamics.

To prepare the system, we poured the grains into the box and gave gentle taps to compact the grains such as to "erase" the structural memory of the pouring and to prepare the system at a given packing fraction. Next, we placed the thin metal lid on the surface and let the laser go through the packing. We left it go for one hour in order to stabilize the laser as well as the initial stress relaxations in the sample. Note that in these experiments we did not put the intruding grain because it would have interfered with the other measurements. Once stabilized, we turned on the piezos at their maximum capacity ($35V_{eff}$, which corresponds to a r.m.s. acceleration measured by the accelerometer of $\langle\gamma^2\rangle^{1/2} = 0.24m/s^2 << g$). After an hour of vibration we changed the voltage value. We continued the vibration changing the voltage each hour, measuring the position of the surface and recording the speckle images during each of these one-hour vibration intervals. Actually, we made two different experiments (labeled experiment 1 and experiment 2) with different voltage variation sequences.

3.3. Preliminary results

3.3.1. Experiment 1 - compaction and microscopic dynamics

The inner frame of figure 8 (left) shows the voltage variations that we followed in this experiment. We began with a *first descent* from $V_{eff} = 35V$ to $V_{eff} = 27.2V$; then, we came back to $V_{eff} = 35V$ and made a *second descent* down to $V_{eff} = 10V$. We did this with the idea of reaching a stationary state during the first strong vibration steps and to compare the measurements for the same voltage values in the second voltage descent. The correlation functions $g_2(t_w, t)$ of figure 8 (left) fit well with a stretched exponential $y(t) = exp(-(t/\tau)^{\alpha})$.

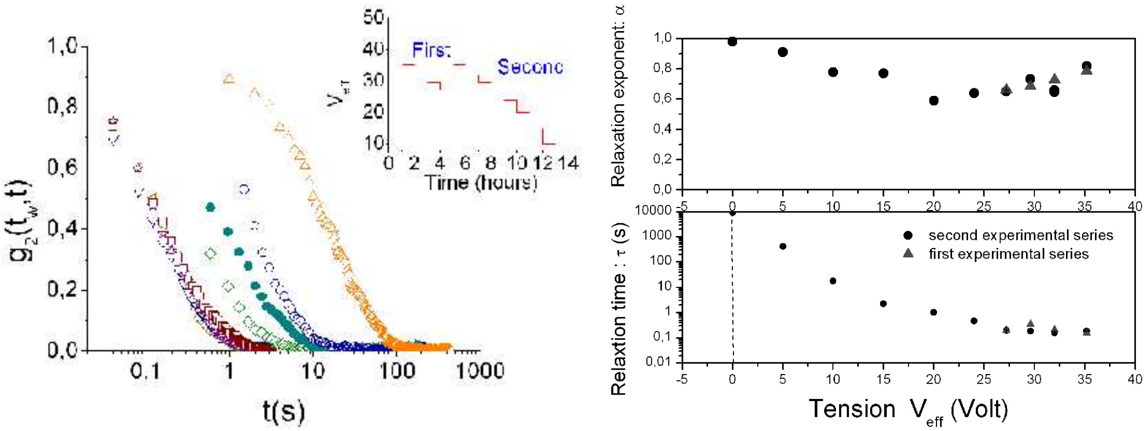

Figure 8. Left: Correlation functions for the second descent of experiment 1: $(\triangleleft)V_{eff} = 35V$, $(\triangledown)V_{eff} = 32V$, $(\bigstar)$ $V_{eff} = 29.6V$, $(\square)V_{eff} = 27.2V$, $(\lozenge)V_{eff} = 24V$, $(\bullet)V_{eff} = 20V$, $(\circ)V_{eff} = 15V$, $(\triangle)V_{eff} = 10V$. Inner frame: Voltage variations in experiment 1: we began with a first descent from 35 to $27.2V$; then, we came back to $V_{eff} = 35V$ to make a second descent down to $V_{eff} = 10V$. Right: Behavior of α and τ, parameters of the fitting stretched exponential to the correlation function $g_2(t,t_w)$, as a function of effective voltage for the first and second voltage descents of experiment 1.

On the right of figure 8 we can see the behavior of α and τ as a function of voltage. From the comparison of the first and second descents we don't observe any ageing effect, since the data corresponding to both of them are similar. Noteworthy, for the value of α other authors [23] have reported a constant value of 0.8 for similar systems.

From the position of the surface we can, in principle, calculate the packing fraction ν and the potential energy E of the system. However, despite the high precision data that we have for the surface position, we can only roughly estimate the corresponding *absolute* value of the packing fraction (5% error). This is due to the lack of precision in determining the total volume of the cell+tweeters. The left of figure 9 (a) shows the compaction dynamics of the system during the first hour of vibration. After an initially "fast" decrease of the height, we indeed observe a slow logarithmic-like compaction process. Note that a stationary state is not yet reached. Plot (b) of the left of figure 9 shows a typical measure of the position of the surface during vibration at $V_{eff} = 35V$. It corresponds to the second descent, i.e. five hours after the beginning of the vibration and though it seems that the system had reached a stationary state, there is still a slow systematic compaction not perceptible at such time scale. Interestingly, the position of the surface seems to undergo wild fluctuations expanding and compacting in an irregular manner. However, the spatial displacement of the level of the surface is of the order of microns, much less than a grain size. So here we are talking about a collective macroscopic behavior since individual grain migration is not possible. This surface dynamics should be associated with the typical size of grain rearrangements in its surrounding (slipping of contacts and rotations) performed more or less randomly per unit time and integrated over the cell height. This is why we

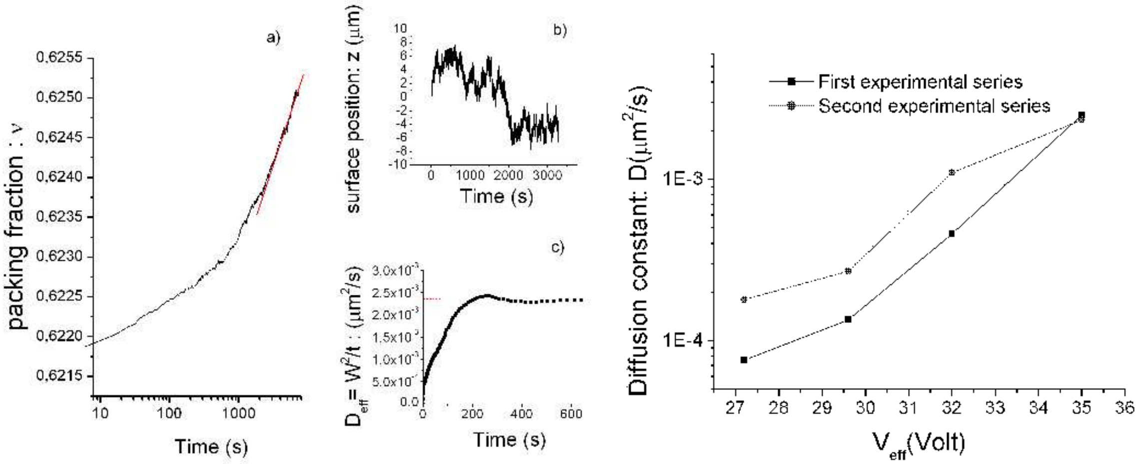

Figure 9. Left: a) Initial compaction at $V_{eff} = 35V$. A steady state is not observed. b) Short time diffusion-like fluctuations of surface's position during vibration. It corresponds to the second descent at $V_{eff} = 35V$. c) Surface's position fluctuates following a simple diffusion; the diffusion constant is calculated from position's roughness. Right: Effective diffusion of the height of the surface vs effective voltage

now investigate the dynamics of the fluctuations more precisely.

From the signal of figure 9 (b) we calculated the roughness $W = \langle (z - \langle z \rangle)^2 \rangle^{(1/2)}$, where z is surface's position, as a function of time and we found that the surface fluctuates as a simple diffusion process since $D_{eff} = W^2/t$ tends to a constant, the effective diffusion constant, for long times (figure 9, c)). In figure 9 right we show this constant for different values of the effective voltage for both experimental series. Now it is clear that there is a difference between the first and the second descent which could be a signature of the ageing of the packing. However a final conclusion is not possible here since the data corresponds to a single realization.

3.3.2. Experiment 2 - Dynamical intermittency

One of the first things we noticed when we began to work with vibrated systems was that the speckle dynamics during vibration was not continously varying but would rather show intermittent or irregular behavior. For a given vibration intensity we observed that the speckle changed with a typical characteristic decorrelation time, but the value of this time would often present big variations depending on which initial speckle pattern was chosen. Basically there were phases where the decorrelation would be regular and steady but others where an intense dynamics would drastically accelerate the speckle decorrelation. Interestingly, this kind of behavior was observed recently in thermal systems near jamming transition by Cipelletti *et al.* [24]. Moreover, these authors have proposed a way to quantitatively characterize the intermittency using the autocorrelation intensity function (eq. 1) obtained from the DWS technique. The idea is to keep fixed the time interval between correlating images t and to vary the reference image t_w. If the speckle dynamics were continuous this analysis would result in a kind of noise around a constant correlation

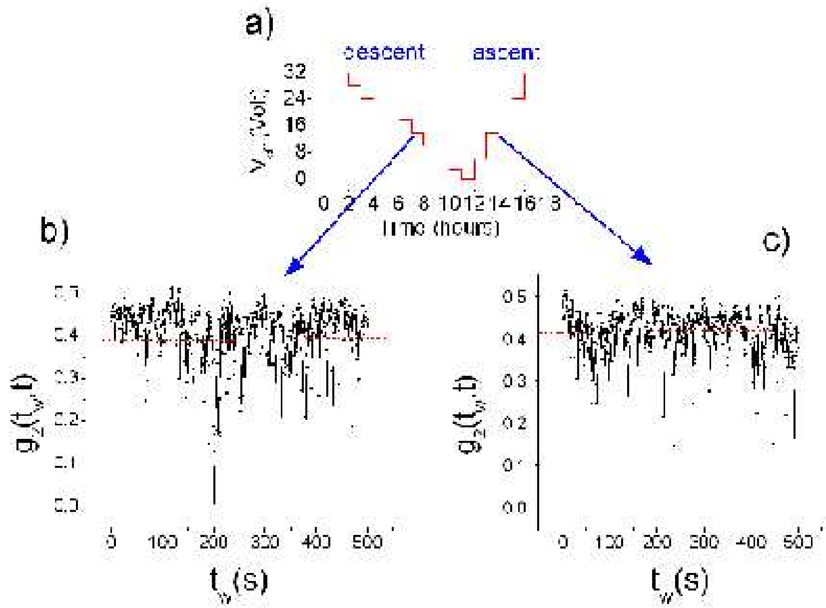

Figure 10. a) Voltage variations in experiment 2. b) Autocorrelation intensity function (eq. 1) for variable t_w and constant $t = 0.5s$ at $V_{eff} = 14V$ of the descending part of voltage variation. c) The same as (b) but for the ascending part. The correlation drops off from its mean value as a result of the intermittent dynamic of the system near jamming transition.

value depending on t. However, huge "catastrophic" events would give low correlation values, highly deviated from the mean. The statistical analysis of such events leads to a quantitative characterization of the systems dynamics [24]. Following these ideas we made an experiment similar to the previous one but with different voltage variations (fig. 10 (a)). In (b) and (c) of figure 10 we observe the autocorrelation intensity function for variable t_w and constant $t = 0.5s$ for the same vibration intensity ($V_{eff} = 14V$), (b) corresponding to the descending part of the voltage variation and (c) to the ascending part. It is possible to appreciate how the correlation frequently drops off from its mean value. In figure 11 is shown the histogram of the data from plots of figure 10. If there was an ageing effect the two histograms should be different, which is not the case. However, the deviation of the histograms from a Gaussian one to the low values of $g_2(t, t_w)$ is an evidence of intermittency [24].

3.3.3. Mobility of an intruding grain

In this experiment we tried to measure the mobility of a grain inside the vibrated granular system by forcing an intruding grain to move trough it. We glued the intruding grain to a fishing thread which passes through the granular assembly and that is tightened by two masses of different weight in an Atwood's machine-like configuration (see figure 7). The

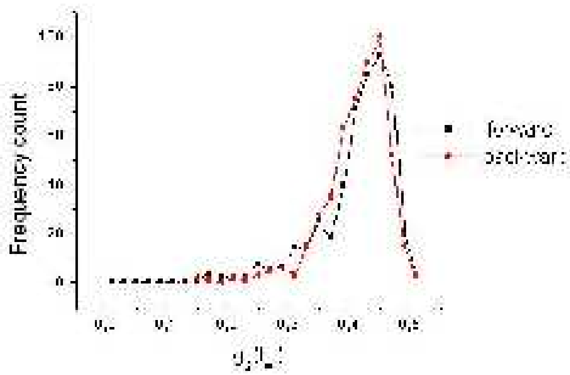

Figure 11. Histogram of the correlation curves of figure 10. The deviation from a Gaussian curve results from intermittency [24]. From comparison of the forward and backward data we don't find evidence of ageing for this particular case.

intruder's position is monitored by an inductive captor that measures the displacement of one of the tightening masses. The size of the intruding grain is of $6mm$ in diameter. Figure 12 shows three different regimes of the mobility as a function of $\Delta M = M_2 - M_1$ (see figure 7). For $\Delta M = 9g$ the intruding grain is initially moving but suddenly gets jammed. A continuous movement around a constant velocity is observed for $\Delta M = 15g$. Finally, for ΔM around $25g$ there is a plastic yield and the intruding grain moves without resistance through the granular material. Although these are only preliminary results they show that this technique allows for interesting mobility measurements.

4. Conclusions

We have shown the results of two experiments of vibration of a granular material, one in 2D and one in 3D, where both macroscopic and microscopic features of the flow can be measured and eventually related. In the case of the two dimensional assembly with free surface, it was also clear that the long time dynamics is dominated by convection and that dispersion due to local self diffusion is not a dominant feature. While moving into the huge convection rolls, the grains would roughly conserve their neighbors for a very long time. We could not measure any self-diffusion characteristics for the whole durations of the experiments and this conclusion still holds even when convection (but not the granular agitation) is suppressed by imposing a lid on the top. Consequently, from these direct observations in 2D, we came to the conclusion that in all standard shaking experiments, the observed compaction steady states could result from a competition between compaction due to vibration and expansion due to convection. Moreover, we stress on two important points. First, the suppression of convection is quite important to a controlled study of compaction dynamics and to access the notion of "effective temperature"more easily. Second, in the very dense phase, the notion of self-diffusion of a particle is unlikely to be

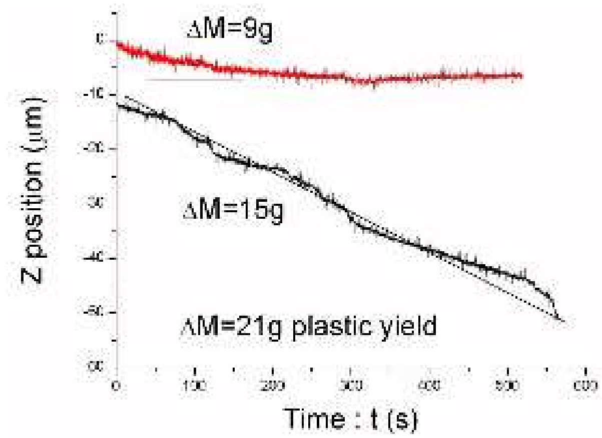

Figure 12. Measurement of the displacement of the intruding grain during vibration for different ΔM.

a relevant parameter suited to characterize the jammed dynamics. Basically, the motions of the grains are localized in the cage formed by their neighbors and their jumps statistics within the cage reflect *collective* modes of reorganization. These dynamical processes are indeed sufficient to create global compaction/decompaction processes without motion of a grain out of its neighbor's cage.

We managed to achieve a convection free vibration in the three dimensional experiment by putting the grains in direct contact with five piezoelectric transducers. Then, we were able to study the compaction dynamics in the weak vibration limit, i.e. imposed by accelerations much smaller than gravity. A study of compaction under this circumstances is quite new. We observed a very slow density relaxation and diffusion of the free surface that we will be able to characterize more properly in experiments actually in progress. Interestingly, the magnitude of volume or density fluctuations indicates that there is no grain diffusion during vibration, thus the compaction and reorganization dynamics of the bulk is solely due to collective features. Another advantage of weak vibrations is that we managed to observe and measure intermittent dynamics which creates a link with results on jammed colloidal phases. This becomes important since, as pointed out by L. Cipelletti et al. [24], temporal heterogeneities are a fundamental feature of the dynamics of jammed systems. Interestingly, surface diffusion as well as intermittent dynamics were also found in stochastic compaction models [25, 26]. Moreover, it has been proposed that a practical way to experimentally measure effective temperature is to analyze intermittent events [27]. These preliminary results are encouraging. We think that we will be able to extract very interesting information from this system once we had done all the calibrations needed and improved our procedures. Also, a central point is to manage to reach the stationary state, which seems not easy since we work with extremely weak vibrations. In fact, one of the things that we want to do is to increase the power injection to the system and to randomize it as much as possible. Certainly, it would be very interesting to couple

together all the different measures that we can make on the system. With this, we could try to relate the microscopic features (DWS and mobility measurements) to macroscopic ones (compaction dynamics and density fluctuations). Of course, the next obvious step is to obtain the measurements of density and its fluctuations (or, equivalently, energy and its fluctuations) to compare them to the numerical results of A. Fierro et al. [11].

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